Optimal Use of Information for Measuring Top Quark Properties

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- **Applied to M_{top} and F_0 measurement using Run I DØ data**

M_{top} (preliminary) = 180.1 ± 5.4 GeV

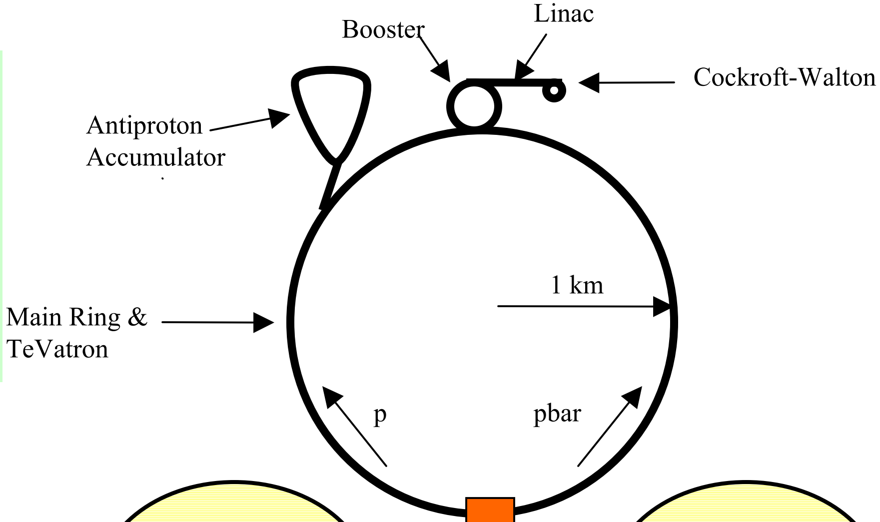
F_0 (preliminary) = 0.56 ± 0.31

Top Quark Production

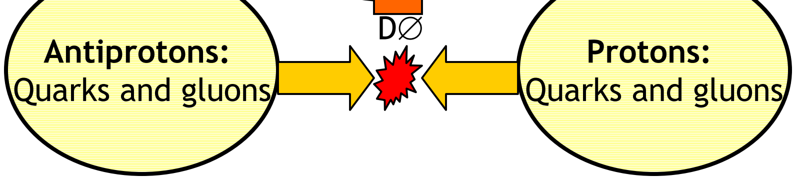
- Discovered in 1995 by D∅ and CDF collaborations at the **Fermilab TeVatron**

Fermilab TeVatron **1992-1996 (Run I)**

- $\sqrt{s}$ =1.8TeV, 900 GeV protons - 900 GeV antiprotons
- 6 x 6 protons-antiprotons bunches

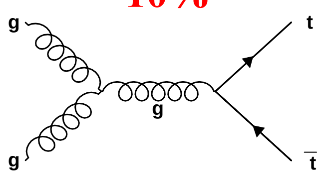


- In proton-antiproton collisions at TeVatron energies, top quarks are primarily **produced in pairs**.
@ $\sqrt{s}$ =1.8TeV:

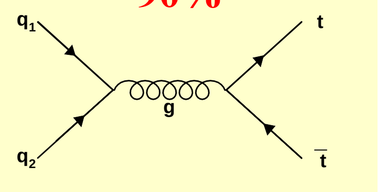


Each parton carries a fraction of the total energy (900 GeV)

~10%

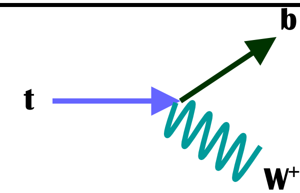


~90%

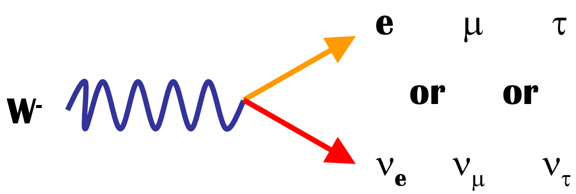


Top Quark Decay

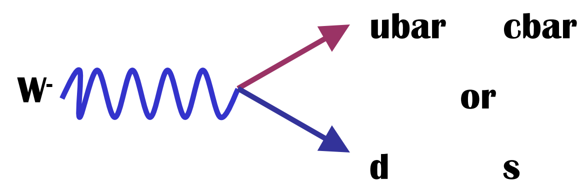
- Each top quark decays weakly: **BR(t⇒Wb) @ 100%**



- W's can decay in any of these ways:



1/9 each



3/9 each

- From a ttbar pair, we have a W+ and a W-. There are 3 main experimental ttbar signatures depending on the decay of the *W* boson:

Dilepton BR(ee+μμ+eμ) = 5%

small background, small statistics

2 leptons, 2 b quarks, 2 neutrinos

Lepton +Jets BR(e+jets,μ+quarks) = 30%

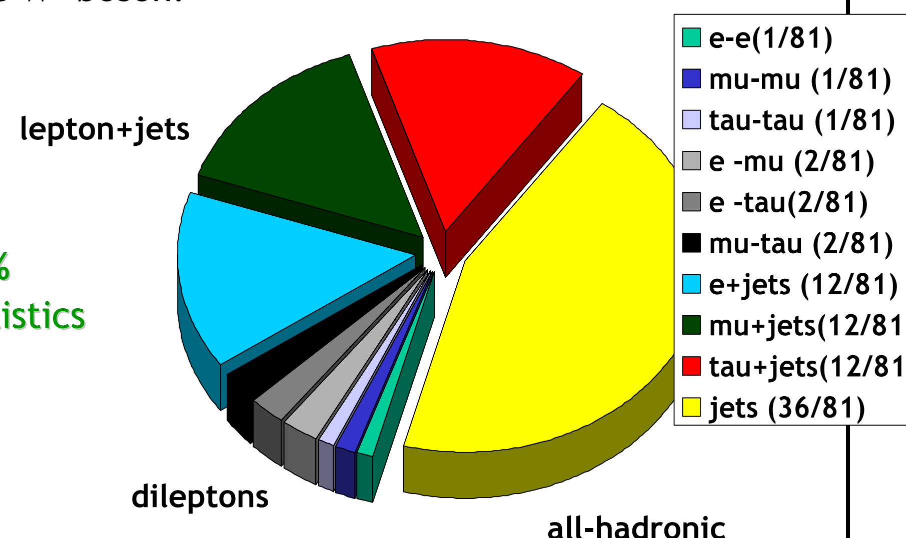
manageable backgrounds, higher statistics

1 lepton, 4 quarks, 1 neutrino

All-Hadronic BR(quarks)=44%

multi-jets background

6 quarks (2 b quarks)



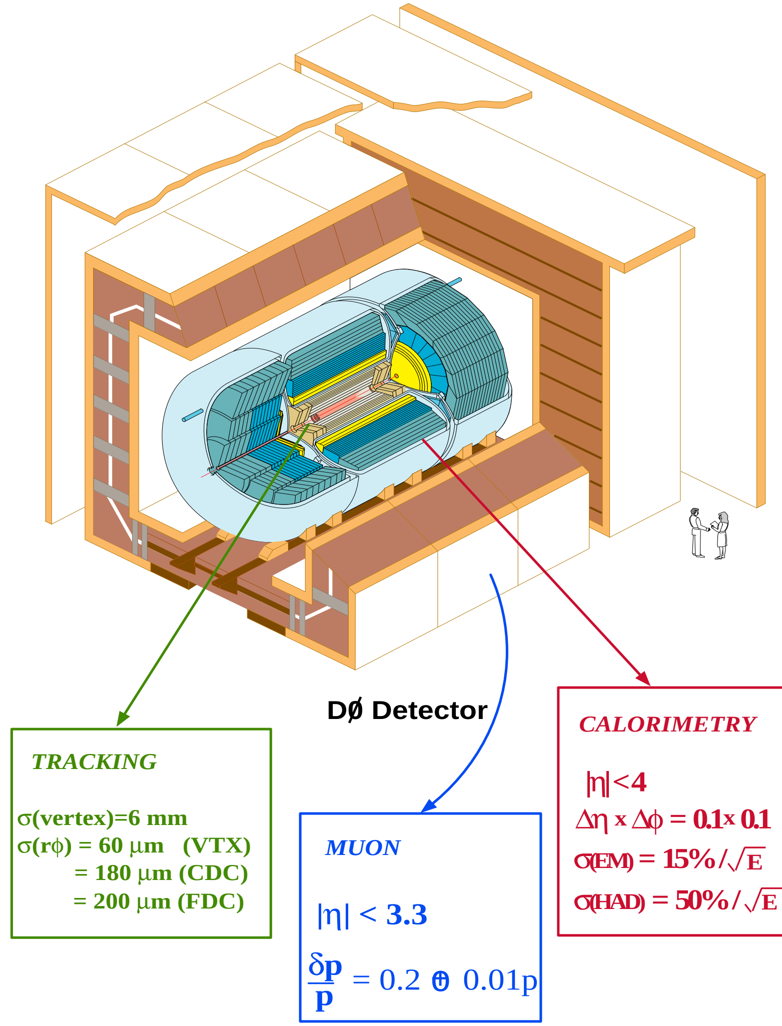
Detecting Top Quarks

- **Detector located around the collision point:**
  1. Measure particle's position, momentum and charge
  2. Type and kinetic energy

- **DØ Run I Detector**

  Starting from center moving outwards:

  - Central tracking system: measures interaction vertex
  - Calorimeters: contain and measure energy and direction of electromagnetic/hadronic particles (electron, photon, jets)
  - Muon Chambers (toroid): charge/momentum of muons



η is proportional to the polar angle, θ

P_T = transverse momentum

Event Topology and Selection Criteria

- **D∅ Statistics Run I (125 pb^{-1})**

Signature: 1 high-P_T lepton, 4 jets (2 b jets), large missing-E_T

More jets coming from gluon radiation, or fewer due to detector inefficiencies, merging of jets, etc

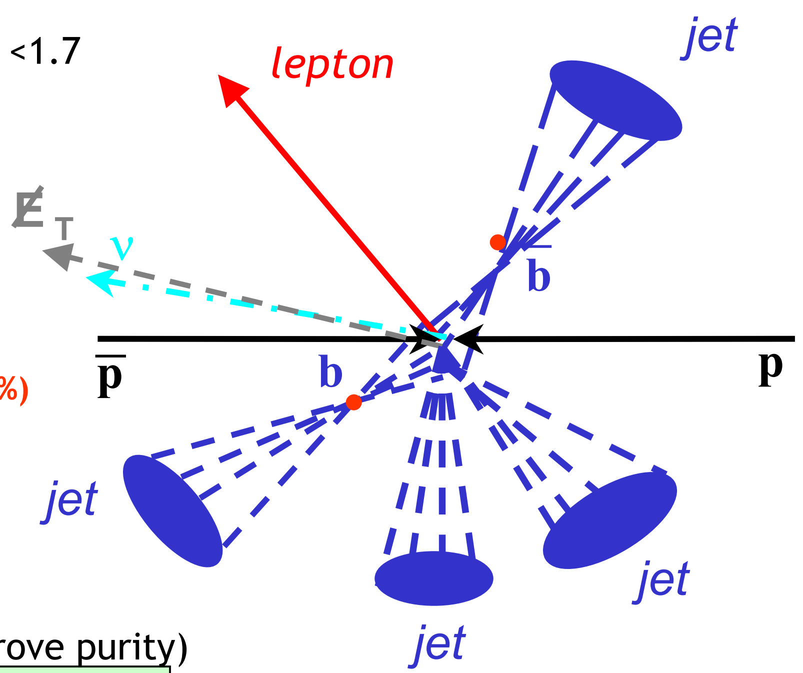
Background: W with associated production of jets

- **Standard Selection:**
  - **Lepton:** E_T>20GeV, $|\eta^e|<2$, $|\eta^\mu|<1.7$
  - **Jets:** ≥4, E_T>15 GeV, $|\eta|<2$
  - **Missing E_T** > 20 GeV
  - "E_T^W"> 60 GeV ; $|\eta_W|<2$

  91 events

  Ref. PRD 58 (1998), 052001

  Background: W+jets (~85%) + multijet (~15%)



- **Additional cuts for this analysis :**
  - 4 Jets only (LO ME)

  71 events

  - Background probability (to improve purity)

  22 events => 12 signal + 10 background

The General Method – the ideal case

In our case $\alpha = M_{top}, F_0$

- We want to find the value of a parameter α

- The best estimate of a **parameter (α)** is achieved comparing the events with the probability from the theory with the data. This is done by maximizing a likelihood:

$$L(\alpha) = e^{-N\int \overline{p}(x;\alpha)dx} \prod_{i=1}^{N} \overline{P}(x_i;\alpha)$$

where x is a set of measured variables

- If we could **access all parton level quantities** in the event (the four momentum for all final and initial state particles), then

$$\overline{P}(x;\alpha) \propto d\sigma$$

That is, we could simply **evaluate the differential cross section as a function of the parameter that we would like to extract for these partons**. In this way we would be using the best knowledge of the physics involved

The General Method – the real case

- In a real experiment, we take the ideal case and **integrate over everything we do not know**. The integration reflects the fact that **we want to sum over all the possible parton variables *y* leading to the observed set of variables *x***

W(y,x) is the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***

d^n σ is the differential cross section

$$\overline{P}(x;\alpha) = \frac{1}{\sigma}\int d^n\sigma(y;\alpha)\underline{dq_1\,dq_2\,f(q_1)\,f(q_2)}W(x,y)$$

f(q) is the probability distribution than a parton will have a momentum ***q***

- In a real experiment with a **real detector**

$$\overline{P}_{measured}(x;\alpha) = Acc(x)\overline{P}_{production}(x;\alpha)$$

where ***Acc(x)*** include all conditions for accepting or rejecting an event

- If we have **background** events with weights c_i

$$\overline{P}(x;c_1,\ldots,c_K,\alpha) = \sum_{i=1}^{K} c_i\overline{P}_i(x;\alpha)$$

Transfer Function W(x,y)

- ***W(x,y)*** probability of measuring ***x*** when ***y*** was produced (***x*** jet variables, ***y*** parton variables):

Energy of electrons is considered well measured

$$W(x,y)=\delta^3(p_e^y-p_e^x)\prod_{j=1}^{4}W_{jet}(E_j^y,E_j^x)\prod_{i=1}^{4}\delta^2(\Omega_i^y-\Omega_i^x)$$

And due to the excellent granularity of the D∅ calorimeter, angles are also considered well measured

where

E^y	energies of produced quarks
E^x	measured and corrected jet energies
p^y_e	produced electron momenta
p^x_e	measured electron momenta
Ω^y_j, Ω^x_j	produced and measured jet angles

- Events with muons are integrated over their resolution

ttbar->l+jets Matrix Element

$$|M|^2 = \frac{g_s^4}{9} F\overline{F}(2-\beta^2 s_{qt}^2)$$

Only qqbar ~90%

no *ttbar* spin correlation included
s_{qt} sine of angle between incoming parton (q) and top quark in the qqbar CM
b top quark's velocity in the qq CM
g_s strong coupling constant

Leptonic decay

$$F = \frac{g_w^4}{4}\left[\frac{m_t^2 - m_{e\bar{\nu}}^2}{(m_t^2 - M_t^2)^2 + (M_t\Gamma_t)^2}\right]\left[\frac{\omega(\cos\varphi_{e\bar{b}})}{(m_{e\bar{\nu}}^2 - M_W^2)^2 + (M_W\Gamma_W)^2}\right]$$

Hadronic decay

$$\overline{F} = \frac{g_w^4}{4}\left[\frac{m_t^2 - m_{d\bar{u}}^2}{(m_t^2 - M_t^2)^2 + (M_t\Gamma_t)^2}\right]\left[\frac{\omega(\cos\varphi_{d\bar{b}})}{(m_{d\bar{u}}^2 - M_W^2)^2 + (M_W\Gamma_W)^2}\right]$$

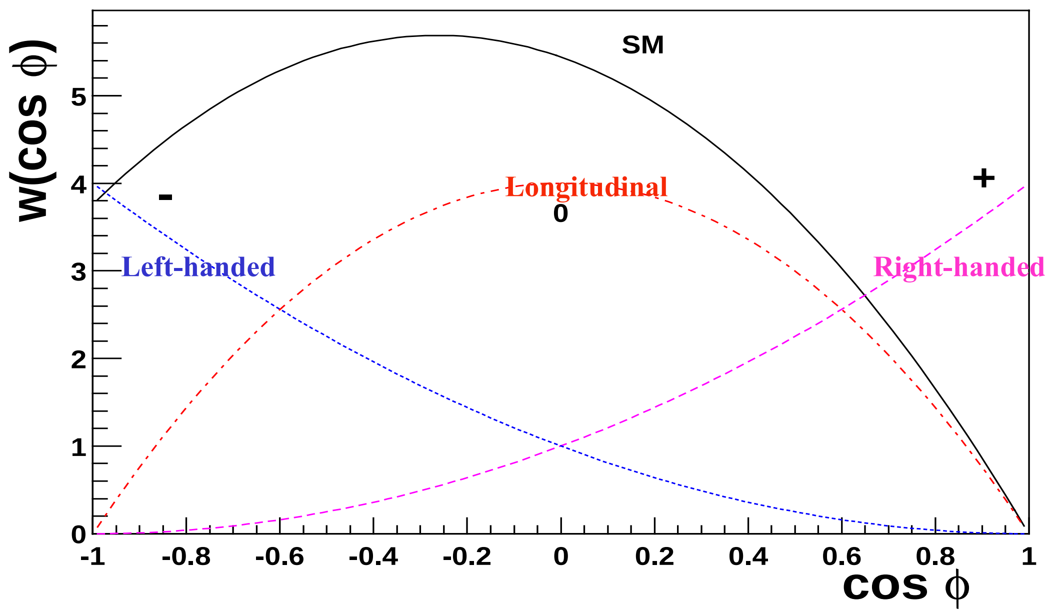
$M_{t,}$ M_W pole top and *W* mass
m_t top mass in any event
m_{en} ,m_{du} invariant mass of the *en* and *du* (or *cs*) system
G_t, G_W top and *W* width
g_W weak coupling constant
w(cos $\varphi_{eb,db}$) angular distribution of the *W* decay

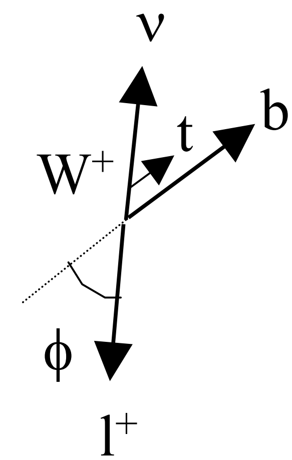
$$\omega(x) = m_t^2\left[(1-x^2) + \frac{m_W^2}{m_t^2}(1+x)^2\right]$$; *x = cos $\varphi_{eb,db}$ in the W frame*

Angular Distribution of Top Decay Products

Left-handed **Longitudinal** **Right-handed**

$$w(\cos\varphi) = F_- \cdot \frac{3}{\ }(1-\cos\varphi)^2 + F_0 \cdot \frac{3}{\ }(1-\cos^2\varphi) + F_+ \cdot \frac{3}{\ }(1+\cos\varphi)^2$$





W rest frame

similar case for the hadronic decay of the W

In SM (with m_b=0),

We want to extract

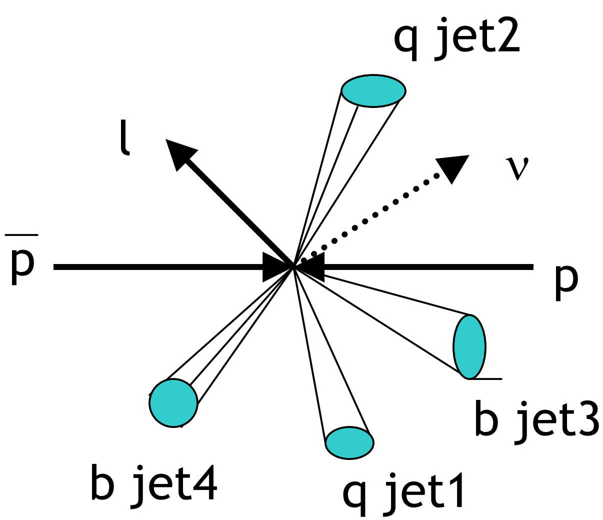
$$F_- = \frac{2\alpha}{1+2\alpha} \qquad F_0 = \frac{1}{1+2\alpha} \qquad F_+ = 0$$

where $\alpha = M_W^2/M_{top}^2$

$F_- = 0.3$ $F_0 = 0.7$ $F_+ = 0$

with M_{top} =175 GeV and M_W=80.4 GeV

Probability for Signal Events



- 2(*in*) + 18(*final*) = **20 degrees of freedom**
- 3(*e*)+8(Ω1..Ω4)+3(P_{in}=P_{final})+1(E_{in}=E_{final}) = **15 constraints**
- 20 – 15 = **5 integrals** => we choose M_{top}, m_W and jet energy of one of the jets because $|M|^2$ is almost negligible, except near the four peaks of the Breit-Wigners within $|M|^2$
- All the neutrino all possible solutions are considered
- Sum over 12 combinations of jets

$$P_{t\bar{t}}(x,\alpha) = \frac{1}{12\sigma_{t\bar{t}}} \int d\rho_1 dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{comb,\nu} |M_{t\bar{t}}(\alpha)|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \phi_6 W_{jet}(x,y)$$

ρ_1 momentum of one of the jets
m_1,m_2 top mass in the event
M_1,M_2 *W* mass in the event
$f(q_1)$,$f(q_2)$ parton distribution function (CTEQ4) for incident partons
q_1,q_2 initial parton momentum
ϕ_6 six particle phase space
$W_{jet}(x,y)$ probability of measuring x when y was produced in the collision

Probability for Background Events

- The background probability is defined only in terms of the main background (*W*+jets, 85%) which proves to be an adequate representation for multijet background

- The background probability for each event is calculated using VECBOS subroutines for *W*+jets

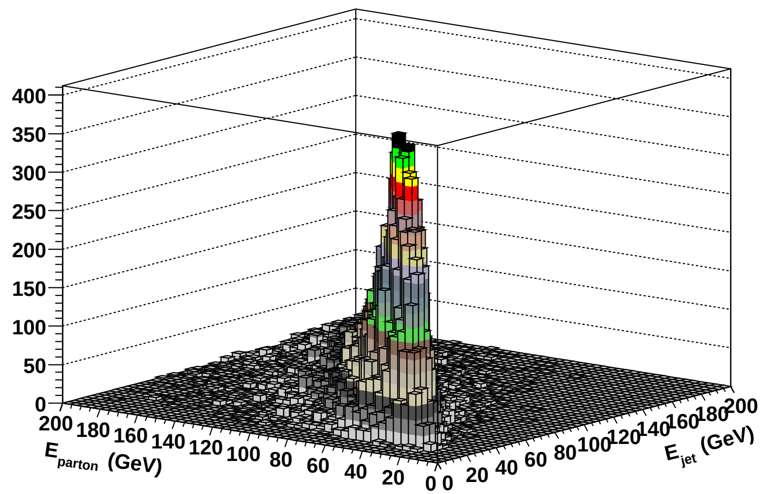
- Same transfer functions for modeling the jet resolutions *W(x,y)* as for signal events

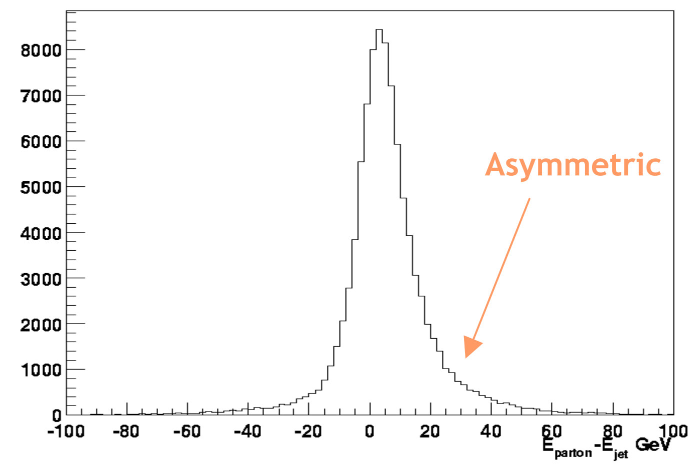
- All permutations are considered, together with the possible values of the z component of the momentum of the neutrino

- Integration done over the jet energies (very slow calculation)

- Monte Carlo method of integration. Integrate until ensure convergence.

Transfer Functions $W_{jet}(x,y)$





- Model the smearing in jet energies from effects of **radiation, hadronization, measurement resolution, and jet reconstruction algorithm**

- Correcting on average, and considering these distributions to be Gaussian can underestimate the jet energy

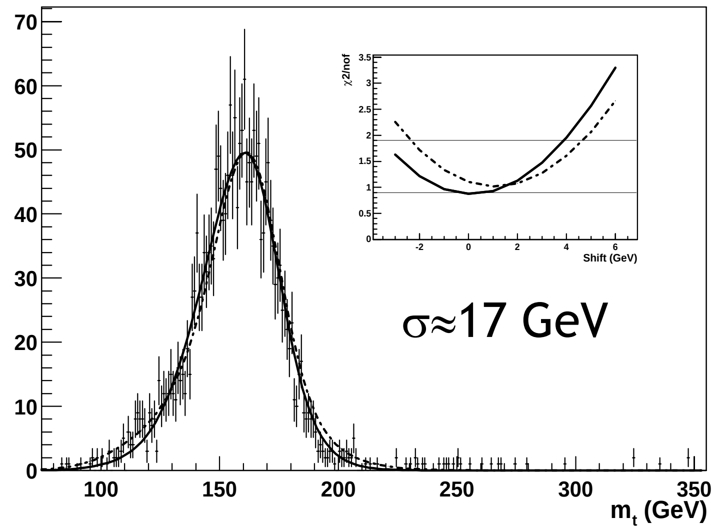
- Use 2 Gaussians, one to account for the peak and the other to fit the asymmetric tails,

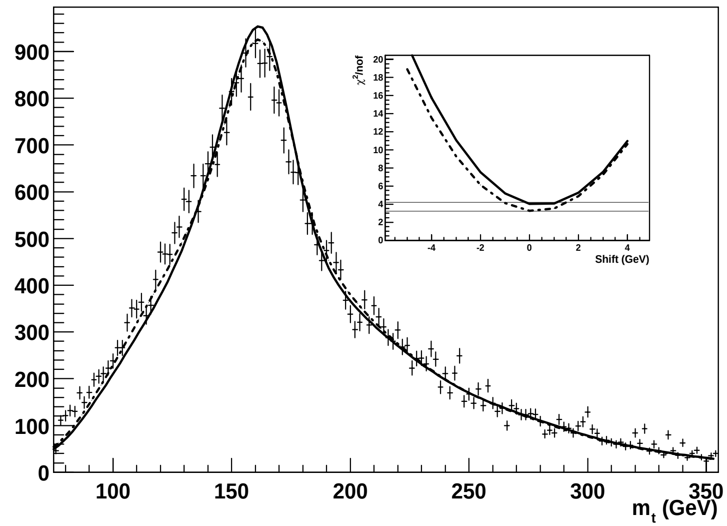
$$W_{jet}(x,y) = \frac{1}{\sqrt{2\pi}(p_1 + p_2 p_5)}[\exp\frac{-(\delta_E - p_1)^2}{2p_2^2} + p_3 \exp\frac{-(\delta_E - p_4)^2}{2p_5^2}] \quad \text{where} \quad p_i = a_i + b_i E_{parton}$$

- Parameters are obtained from maximizing a likelihood and using different samples of Monte Carlo events where jets were matched to partons
- *b* and light quark jets

Best Case Scenario

Worst Case Scenario





Top Mass

Histogram: HERWIG Monte Carlo DØ Run I simulation and reconstruction with standard selection criteria

Solid line: Exact calculation using the transfer functions

- Only events matched to partons (50%) are used in these histograms
- Only correct permutation is considered

- Events with exactly 4 jets
- No matching to partons was required
- 12 permutations are considered

Approximations in the probabilities definitions (things to do better with more statistics)

- **Only *ttbar* from *qqbar* production:** it does not include 10% of ttbar events that are produced by gluon fusion
- **Only *W*+jets background:** that is ~85% only of the background
- **Leading-Order ttbar matrix element:** no extra jets, constrains our sample to have only 4 jets

$$P_0(x; c_1, c_2, \alpha) = c_1 P_{ttbar}(x; \alpha) + c_2 P_{W+jets}(x)$$

After these approximations, the likelihood function used is

$$-\ln L(\alpha) = -\sum_{i=1}^{N} \ln\left[c_1 P_{ttbar}(x_i; \alpha) + c_2 P_{W+jets}(x_i)\right] + N \int A(x)\left[c_1 P_{ttbar}(x; \alpha) + c_2 P_{W+jets}(x)\right] dx$$

Depends on α

Constant

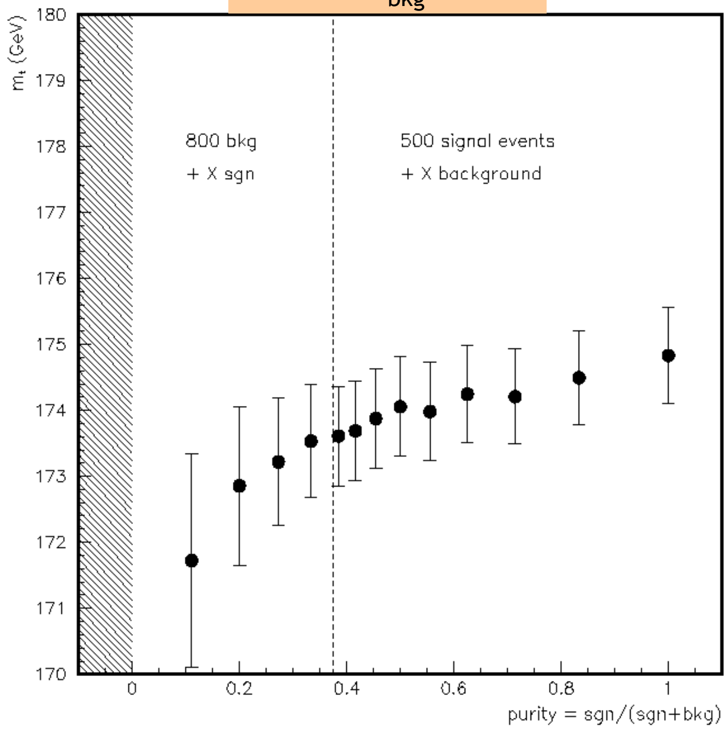
The values of c_1 and c_2 are optimized, and the likelihood is normalized automatically at each value of α

Calculated in two different ways using Monte Carlo method of integration

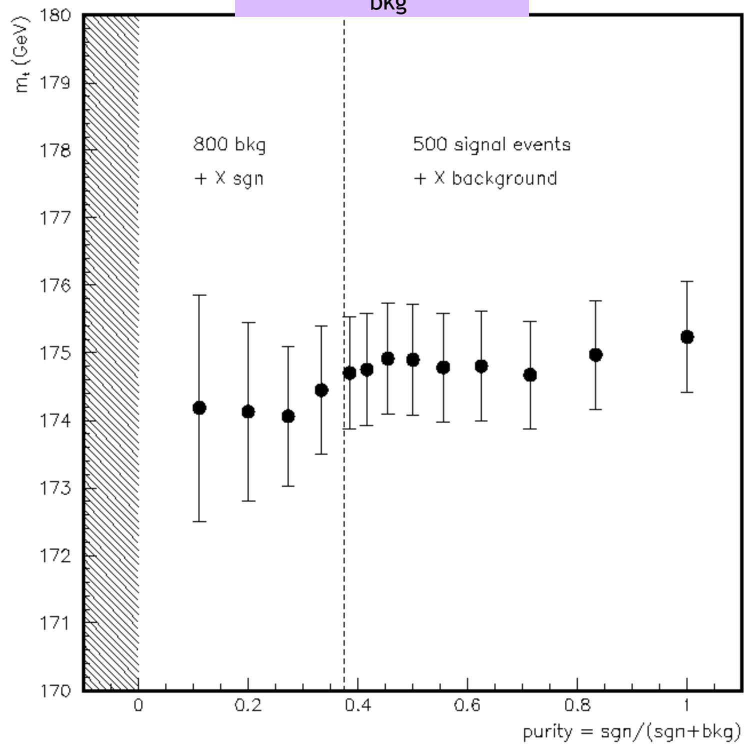
Blind Analysis, purified sample

- This analysis was defined by MC studies, without looking at the data sample
- One of the checks indicated that there could be a shift introduced by background contamination

Before $P_{bkg}<10^{-11}$



After $P_{bkg}<10^{-11}$

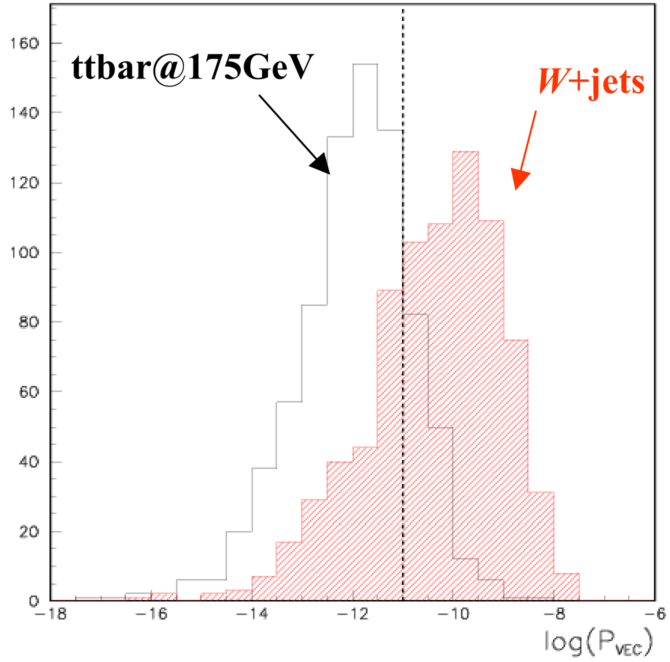


Extra Selection in P_{bkg}

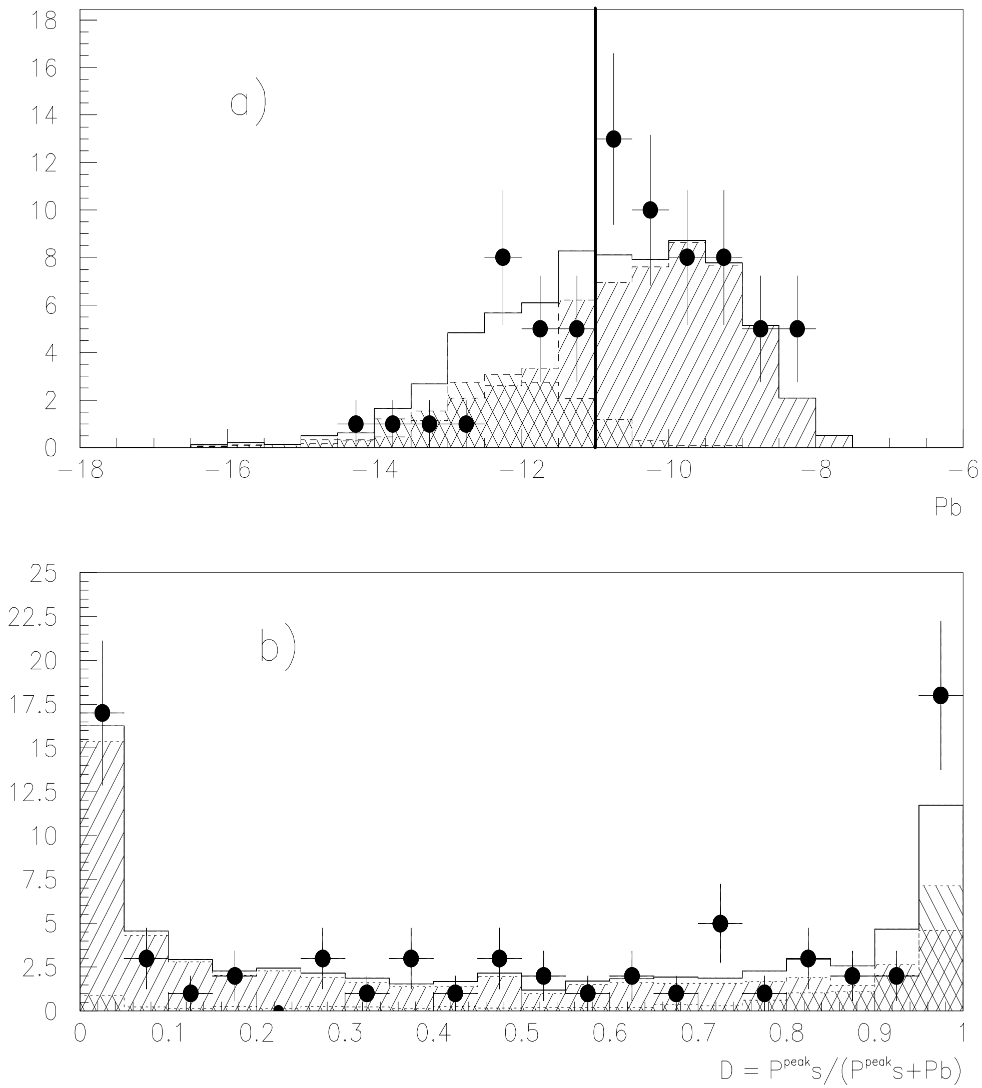
- In order to increase the purity of signal another selection is applied on P_{bkg}, with efficiencies:

  ε_{ttbar} = **0.70**,
  ε_{W+jets} = **0.30**,
  $\varepsilon_{multijets}$ = **0.23**

- We select on $P_{bkg}<10^{-11}$, according to a previous analysis done with this method to measure the top mass



Signal/Background Discrimination



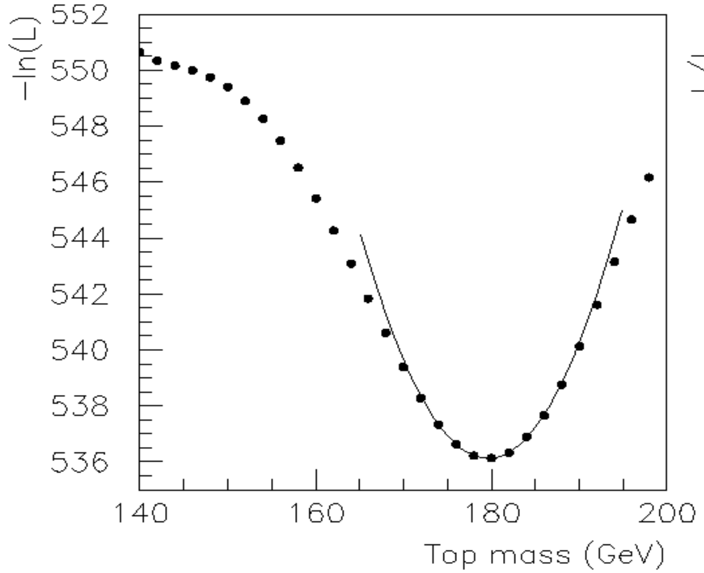
- Comparison of (16 Signal + 55 Background) MC and data sample

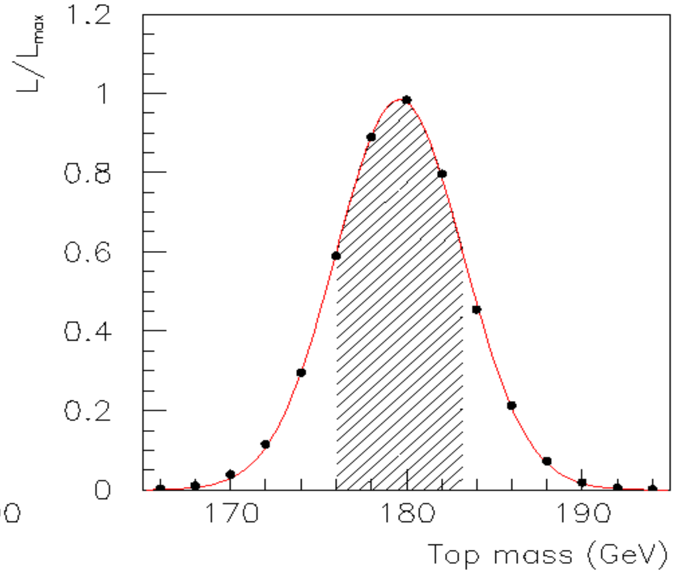
a) Background probability comparison between data (dots) and MC (histogram).

b) Signal probability comparison between data (dots) and MC (histogram) in the form of a discriminant

$$D = P_{signal}/(P_{signal}+P_{background})$$

Preliminary Measurement of M_{top} with DØ Run I Data





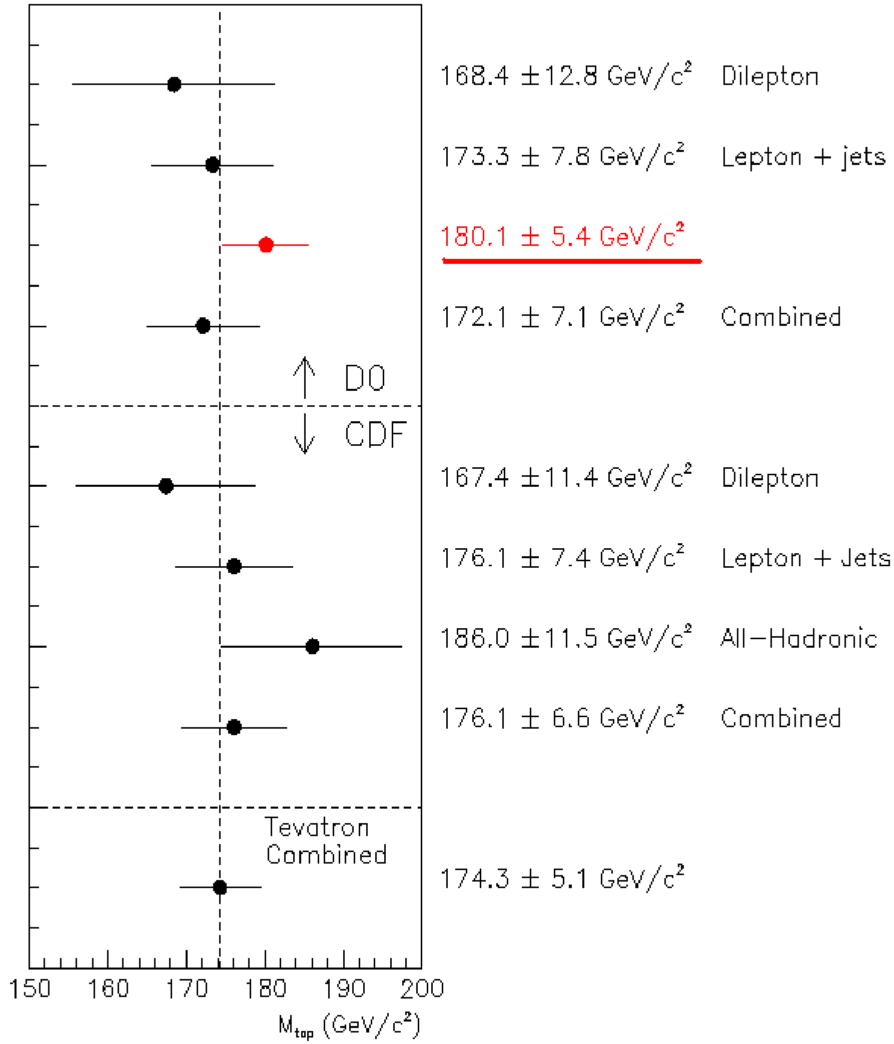
$$M_{top}\ (\text{preliminary}) = 180.1 \pm 3.6_{stat} \pm 4.0_{syst}\ \text{GeV}$$

- This new technique improves the statistical error on M_{top} from 5.6 GeV [PRD 58 52001, (1998)] to 3.6 GeV
- **This is equivalent to a factor of 2.4 in the number of events**

MC	Signal model	1.5 GeV
	Background model	1.0 GeV
	Noise and multiple interactions	1.3 GeV
DATA	Jet Energy Scale	3.3 GeV
	Parton Distribution Function	0.2 GeV
	Acceptance Correction	0.5 GeV

New [preliminary] Result

- The relative error in this result is 3%, compare to 2.9% from the previous CDF and DØ combined average for all channels

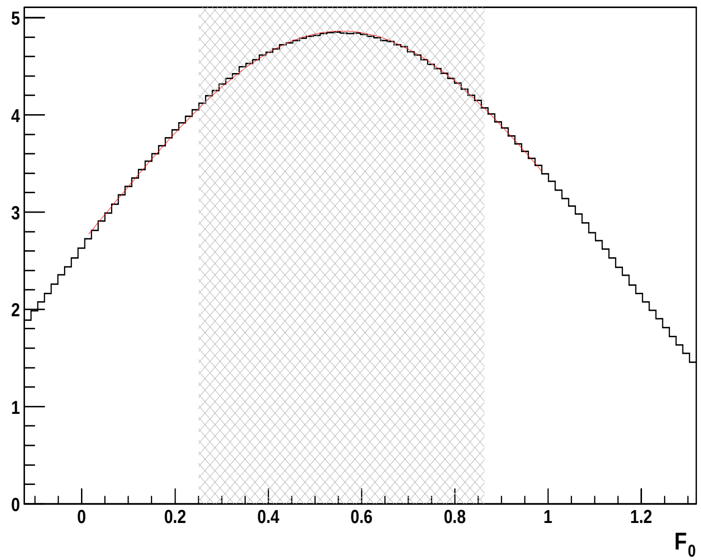


Preliminary Measurement of F_0 with DØ Run I Data

- Uncertainty on the top mass translates into a systematic error on the measurement of F_0
- We integrate over M_{top} from 165 to 190 GeV (no prior)

$$L(F_0) = \int L(M_{top}, F_0)\,dM_t$$

- Integrated over μ resolution
- 35 ***e***+jets candidates
- 36 μ+jets candidate

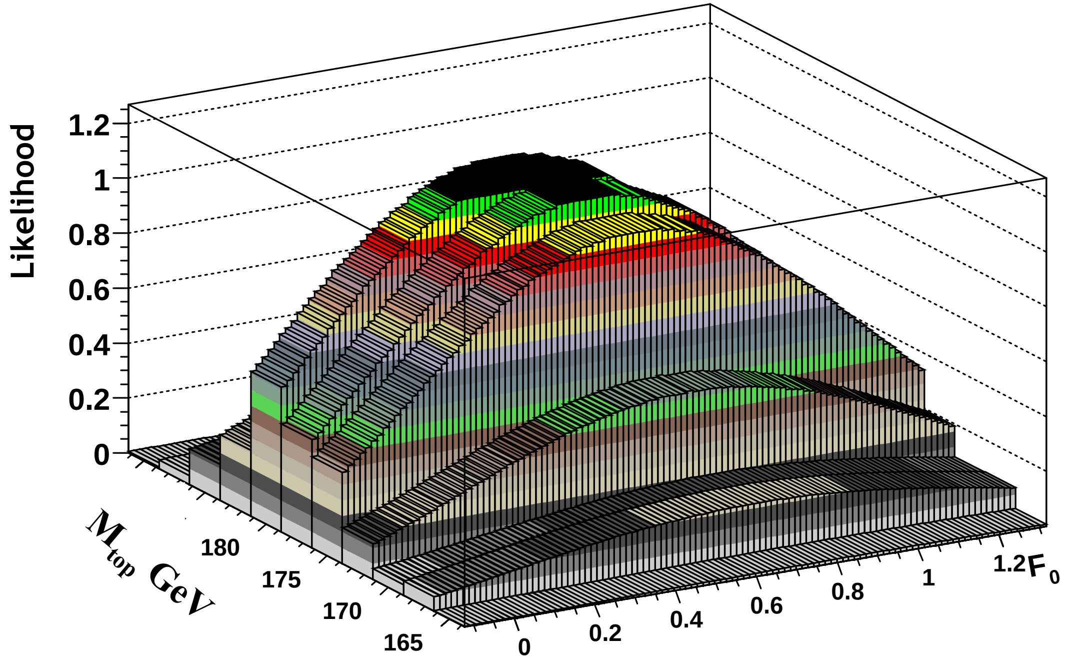


$F_0 \pm \delta F_0(\text{Stat+ } M_{top}) = 0.558 \pm 0.306$

	Statistics + M_{top} uncertainty	0.306
From data	Jet Energy Scale	0.014
From data	Parton Distribution Function	0.007
From data	Acceptance-Linearity Correction	0.021
From Monte Carlo	Background	0.010
From Monte Carlo	Signal Model	0.020
From Monte Carlo	Multiple Interactions	0.009
From Monte Carlo	ttbar Spin Correlations	0.008

Two-dimensional Probability - M_{top}, F_0

- Assuming F_0= 0.7 (SM), **M_{top} is measured** to be 180.1 ± 3.6 GeV (shift of 0.5 GeV applied)
- Assuming M_{top}=175 GeV, **F_0 is measured** to be 0.599 ± 0.302 (linearity response applied)



Conclusions

- This method allows us to extract M_{top} and F_0 using the maximal information in the event:
  - ✓ Correct permutation is always considered (along with the other eleven)
  - ✓ All features of individual events are included, thereby well measured events contribute more information than poorly measured events

- We made use of many approximations, LO ME and parameterized showering, we calculated the event probabilities, and measured:

M_{top}(preliminary)=180.1 ± 3.6 (stat) ± 4.0 (syst) GeV

F_0 (preliminary)= 0.56 ± 0.31

- A complete calculation has to include:
  - the production of extra jets due to radiation, merging and/or splitting of jets
  - calculation of probabilities for every background process